Examining the sensitivity of the DUNE experiment to neutrino oscillation physics and beyond standard model effects

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Introduction

- Atmospheric neutrinos
- Simulation Details
- Oscillation Physics and Phenomenology
- Sensitivities
  - Mass hierarchy
  - CP violation
  - Non standard interactions (NSIs)
- Conclusion
All analysis done here is solely from atmospheric neutrinos.

This work formed a considerable part of my Masters project with Andy Blake.

A mixture of 10,000,000 neutrinos and anti-neutrinos are simulated - results are then scaled by expected detector numbers in 400kt yrs.

In this time we would expect 48,000 events.

Flux and interactions are simulated in DUNE far detector using GENIE.

Pseudo-reconstruction with Gaussian smearing is applied for the detector.
Earth Model

Figure: Earth model used in simulation
Sensitivity calculations

- Separated Electrons and Muons
- Binning scheme was optimised to maximise sensitivity and remove empty bins
- Overall data set was split into two to ensure statistically independent samples
- Analysis only includes systematic uncertainties
- Plots generated depending on oscillation physics and are then compared to reference values using a log-likelihood function (which has been converted to a $\chi^2$ in the plots for interpretive reasons)
Figure: Sensitivity of DUNE to CP violation for 400kt yr exposure using atmospheric neutrinos.
**Figure:** Muon neutrino oscillation probabilities for two hierarchies.
Figure: Sensitivity of DUNE to CP violation for 400kt yr exposure using atmospheric neutrinos.
Figure: Muon neutrino oscillation probability difference between when $\delta_{CP} = \pi$ and when $\delta_{CP} = 0$. 
Non standard interactions (NSIs) (1)

- Standard matter effects Hamiltonian:

\[ \hat{H}_{\text{matter}} = \frac{1}{2E_{\nu}} U \begin{pmatrix} m_1^2 & 0 & 0 \\ 0 & m_2^2 & 0 \\ 0 & 0 & m_3^2 \end{pmatrix} U^\dagger + \begin{pmatrix} V \\ 0 \\ 0 \end{pmatrix} \]

- Additional beyond standard model physics adds additional term:

\[ \sqrt{2} G_F N_e \begin{pmatrix} \epsilon_{ee} & \epsilon_{e\mu}^* & \epsilon_{e\tau}^* \\ \epsilon_{e\mu} & \epsilon_{\mu\mu} & \epsilon_{\mu\tau}^* \\ \epsilon_{e\tau} & \epsilon_{\mu\tau} & \epsilon_{\tau\tau} \end{pmatrix} \]

- Oscillation code is using João Coelho’s oscillation calculator
Table: Experimental limits at 90% level on NSI parameters from existing data\(^4\) and predicted from DUNE.


<table>
<thead>
<tr>
<th>Parameter</th>
<th>Current Limit</th>
<th>DUNE limit (NH)</th>
<th>DUNE limit (IH)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(</td>
<td>\varepsilon_{ee}</td>
<td>)</td>
<td>&lt; 4.2</td>
</tr>
<tr>
<td>(</td>
<td>\varepsilon_{e\mu}</td>
<td>)</td>
<td>&lt; 0.33</td>
</tr>
<tr>
<td>(</td>
<td>\varepsilon_{e\tau}</td>
<td>)</td>
<td>&lt; 3.0</td>
</tr>
<tr>
<td>(</td>
<td>\varepsilon_{\mu\mu}</td>
<td>)</td>
<td>&lt; 0.068</td>
</tr>
<tr>
<td>(</td>
<td>\varepsilon_{\mu\tau}</td>
<td>)</td>
<td>&lt; 0.33</td>
</tr>
<tr>
<td>(</td>
<td>\varepsilon_{\tau\tau}</td>
<td>)</td>
<td>&lt; 21</td>
</tr>
</tbody>
</table>
Figure: Muon neutrino oscillation probabilities for two hierarchies.
Figure: Sensitivity of DUNE to parameter $\varepsilon_{e\mu}$ for 400kt yr exposure using atmospheric neutrinos.
Current work

- Proton tagging
- Electron tagging
- $y$ - distribution
  
  $y = 1 - \frac{E_l}{E_\nu}$
Conclusion

- Measuring unknowns in neutrino physics with atmospheric neutrinos.
- Improve beyond standard model limits.
- Main sensitivity originates from the matter effects including resonances.
- Any questions?